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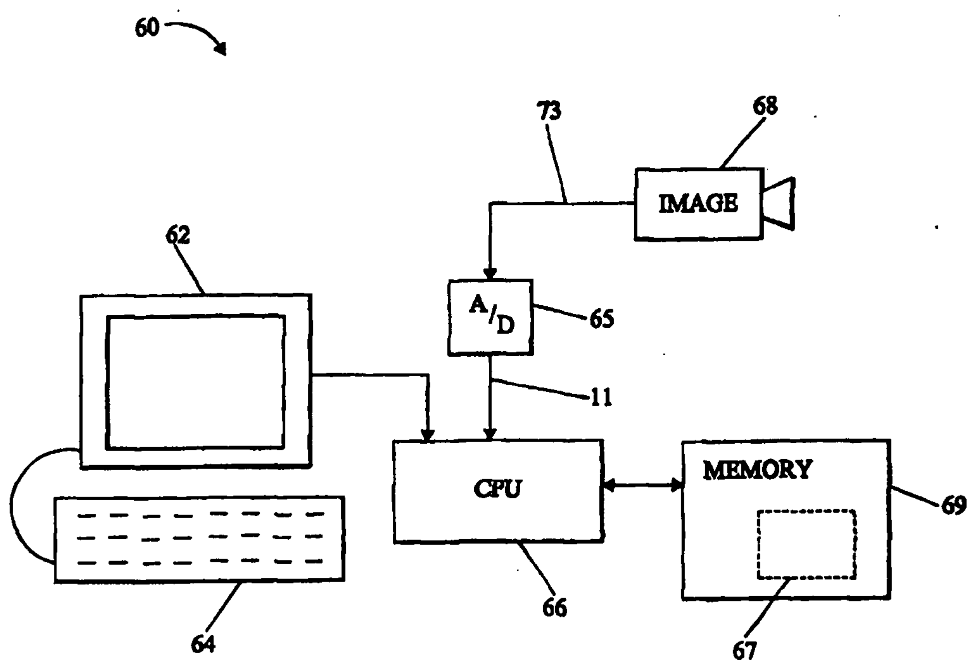

(57) Abstract

An apparatus and method enhances a signal by scaling the local maxima of the wavelet transform coefficients of the signal. The remaining wavelet transform coefficients are then replaced by adjusted values such that: the signal corresponding to the inverse wavelet transform of the scaled local maxima and the adjusted values defines an enhanced version of the signal.

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METHOD AND SYSTEM FOR ENHANCING AN IMAGE

Background

This invention relates generally to the field of signal processing and in particular to the application driven enhancement of a signal by scaling and adjustment of the wavelet transform coefficients associated with that signal.

A computer system typically incorporates a monitor for the display of a signal representative of an image. In such a system, the image displayed on the monitor is frequently a digital representation of an analog image. To obtain such an image, the computer system divides the analog image into a large number of picture elements or "pixels," each of which corresponds to a small portion of the original image. This causes a loss of resolution in the displayed image. It is beneficial, therefore, to enhance the displayed image so as to render the digital representation of the image more faithful to the original analog image.

For signals representative of a video image, these pixels are treated as forming a rectangular array consisting of rows and columns. The location of a pixel within this rectangular array corresponds to the location of the portion of the original image associated with that pixel. Thus, by referring to the row and column it occupies within the rectangular array, one can uniquely identify a pixel and determine its location within the original image.

A result of arranging pixels into a rectangular array is that each pixel has adjacent neighbors. A pixel in the interior of the array has four adjacent neighbors. Except for those four pixels marking the corners of the array, a pixel at an edge has three adjacent neighbors. The four pixels marking the corners of the array each have two adjacent neighbors.

In a digital representation of an image, each pixel is assigned a numerical value. For a monochrome image, this value typically corresponds to the brightness of the portion of the image corresponding to that pixel. For a color image, this value typically corresponds to the amount of red, green or blue in the portion of the image corresponding to that pixel.

The arrangement of pixels into an array and the assignment of values to each pixel as described above enables a computer system for performing image enhancement to treat the rectangular array of pixels as samples $f(x_i, y_i)$ of a two-dimensional function $f(x, y)$ which maps from a domain consisting of the set of all points in the image (the spatial domain) to a range consisting of the set of all brightness values in the image.

Each object within an image can be divided into edge pixels which correspond to the edges of objects with the image and interior pixels which correspond to the interiors of objects within the image. The edge pixels define the overall shape of the object whereas the interior pixels combine to show the texture of the object. Where the shape and location of an object are of interest, a computer system for image enhancement can amplify the edge pixels or attenuate the interior pixels, thereby rendering the edges more conspicuous. A prerequisite for a successful image enhancing system of this type is that the computer system be capable of identifying an edge.

A pixel can generally be classified as an edge pixel by observing the difference between the value associated with that pixel and the values associated with its neighbors. For example, if each pixel in a row has a high value and each pixel in an adjacent row has a low value, one can infer that the row containing that pixel forms a horizontal edge and that therefore every pixel in that row is an edge pixel. Conversely, if a pixel has a value similar to those of all its adjacent neighbors, one can infer that that pixel is an interior pixel.

Since the rectangular array of pixels can be considered samples $f(x_i, y_i)$ of a two-dimensional function $f(x, y)$, the concept of searching for sudden changes in the pixel values can be likened to the process of searching for local maxima of the magnitude of the gradient vector $\nabla f(x,y)$ associated with that function. The direction of the edge can then be associated with the direction of the gradient vector $\nabla f(x,y)$. An image enhancement system that identifies edge pixels by using the gradient vector in this way is said to operate in the spatial domain.

Having located an edge, typical spatial domain image enhancement systems enhance that edge by, for example, rendering it in a different color or multiplying each pixel at an edge by a constant. This results in an image having an unnatural appearance resulting from enhancing only the edges of an image and leaving the remainder of the image untouched.

The image function $f(x, y)$ can also be represented by a weighted sum of complex exponentials. This alternate representation of the image, referred to as a frequency domain representation, can be obtained by performing a fast Fourier transform (FFT) on the samples $f(x_i, y_i)$ of the image function. In this representation, the exponent of the complex exponential corresponds to the spatial frequency of the image and the weighting coefficients, which can be complex numbers, correspond to the amount of that spatial frequency in the image. The set of coefficients forms the frequency spectrum of the image.

Since high frequency coefficients generally correspond to discontinuities or edges in an image, an image enhancement system employing the FFT can detect edges in that image by identifying high frequency components in the frequency spectrum of that image.

Although the frequency spectrum obtained by performing an FFT on the original image enables an image enhancement system to detect the existence of an edge, it does not enable the system to determine where on the image the edge is located. This is because the Fourier transform provides the system only with the magnitude and phase corresponding to each frequency component of the original image. Consequently, the options available in such a system for enhancing edges in an image are limited. Merely boosting the high frequency components of the transform and then evaluating the inverse transform of the result often yields an image laced with stripes or bands at unpredictable locations.

The wavelet transform, like the Fourier transform, provides a technique for decomposing a signal into a weighted sum of orthogonal basis functions. However, unlike the Fourier transform which uses complex exponentials as basis functions, the wavelet transform uses a set of basis functions, referred to as "wavelets," which can be non-zero only for a finite interval. A set of basis functions having this property is said to have "compact support." The general theory of wavelet transforms is set forth in Daubechies, "The Wavelet Transform, Time-Frequency Localization and Signal Analysis," *IEEE Transactions on Information Theory*, vol. 36, no. 5, Sept. 1990 which is hereby incorporated by reference. A computationally efficient process for carrying out both the wavelet transform and its inverse, is described in Mac A. Cody, "The Fast Wavelet Transform," *Dr. Dobb's Journal*, April 1992, pp. 16-28 which is also hereby incorporated by reference.

As is the case with Fourier transforms, a local maximum of the wavelet transform coefficients of an image corresponds to the presence of a high frequency component in the image. Unlike the Fourier transform, however, the spatial location of that high frequency component within the image, if basis functions having compact support are used in the wavelet transform, corresponds to the location of the high frequency coefficient within the array of wavelet transform coefficients. Thus, unlike the Fourier transform, the wavelet transform coefficients can carry information about both the presence of a high frequency component in the image and the location of that component within the image. In this way, the wavelet transform can perform edge detection.

Although the wavelet transform can readily locate an edge, the problem of rendering that edge conspicuous remains. Merely perturbing the wavelet transform of an image by boosting the local maxima of the wavelet transform coefficients can result in rendering the inverse wavelet transform so different from the original image as to be useless. Accordingly, there still exists a need in the art for employing wavelet transforms to better define edge regions in an image.

Summary of the Invention

What is necessary and desirable is a method and system for boosting the local maxima of the largest wavelet transform coefficients and then adjusting the remaining wavelet transform coefficients in such a way as to preserve the integrity of the inverse wavelet transform of the result.

The invention encompasses a signal enhancement system and method for enhancing a signal represented by its wavelet transform coefficients. This is accomplished by assigning alternative values to those wavelet transform coefficients sharing a selected property and then assigning corresponding adjustment values to those coefficients lacking the selected property. These adjustment values are chosen such that the resulting coefficients are wavelet transform coefficients of an enhanced version of the original signal.

According to one aspect of the invention, alternative values are optionally assigned to the local maxima of the wavelet transform coefficients by multiplying those values by a scaling constant. This choice of a selected property tends to emphasize high frequency components in a corresponding section of the signal. However, the choice of a selected property and the manner in which an alternative value is assigned can be changed depending on what features of the signal are to be enhanced.

Similarly, the method by which the adjustment value is assigned to those coefficients lacking in the selected property can be adjusted to the particular application. For example, the adjustment value is optionally arrived at by minimizing a particular error. However, other types of error can be minimized without departing from the scope of the invention.

These and other features, aspects, and advantages of the invention will be better understood with reference to the following description and the accompanying drawings in which:

Description of the Drawings

FIG. 1 depicts the overall architecture of a computer system implementing the signal enhancement system of the invention;

FIG. 2 is a block diagram showing the signal enhancement system of the invention connected to a multistage wavelet transform filter;

FIG. 3 depicts the internal architecture of the signal enhancement system depicted in FIG. 2;

FIG. 4 shows the frequency responses of the high pass filters associated with the first two stages of the multi-stage wavelet transform filter depicted in FIG. 2;

FIG. 5 shows, in schematic form, the result of digitizing an image; and

FIG. 6 shows two signal enhancement systems as depicted in FIG. 2 connected in series.

Description of the Illustrated Embodiment

FIG. 1 depicts a signal enhancement system **60** consisting of a central processing unit ("CPU") **66** which includes a processor for executing programmed instructions. The CPU **66** is in communication with a memory unit **69**. The memory unit **69** can be a volatile memory, such as RAM or it can be a non-volatile memory for long term storage of information. The CPU **66** is also in communication with: an analog to digital converter **65** connected to a signal source **68**, such as a video camera, a microphone, a scanner, a photocopy machine or a facsimile machine; an output device **62**, such as a monitor, speaker, or printer; and an input device, such as a keyboard, **64** for communicating instructions from a human operator to the CPU **66**.

The memory unit **69** contains within it a digital representation of programmed instructions **67** for carrying out the signal enhancement method of the invention on a signal supplied by the signal source **68** and digitized by the A/D converter **65**. The method to be carried out by these programmed instructions is best understood with reference to FIG. 2 which shows the signal enhancement system of the invention operating on the output of a multi-stage wavelet transform filter.

The invention begins with the creation of a digitized representation **11** of a signal hereafter referred to as the "original signal." This can be supplied to the CPU **66** by passing the output **73** of an analog image source **68** through an analog to digital converter **65**. FIG. 5 shows an analog image **76** corresponding to the analog output

signal **73** of an analog signal source **68**. The analog output signal **68** is digitized by an A/D converter **65** to generate an original signal **11** representative of a video image . The original signal **11** can be representetd by a rectangular array **11a** of picture elements, or "pixels," arranged in rows and columns. Each pixel **74** is identifiable by its row **74R** and its column **74C**. Additionally, each pixel can have adjacent pixels **74N**, **74S** occupying the same column and adjacent pixels **74E**, **74W** occupying the same row.

Referring again to FIG. 2, the original signal **11** is passed through a first low-pass filter **42a** and through a first high pass filter **41a**. Together, the first low-pass filter **42a** and the first high-pass filter **41a** comprise the first wavelet transform ($j = 1$) **50a** of a first multistage wavelet transform filter **50**. The pass bands associated with these filters are described below.

The output of the first low pass filter **42a** is then passed through a second low pass filter **42b** and through a second high pass filter **41b** which together form the second wavelet transform ($j = 2$) **50b** of the first multistage wavelet transform filter **50**. The output of this second wavelet transform **50b** can then be passed to succeeding wavelet transform filters **50c**, **50d** in the manner depicted in FIG. 2.

Meanwhile, the outputs of the high pass filters **41a, 41b, 41c, 41d** are passed directly to the output of the first multistage wavelet transform filter **50**. The overall output of the first multistage wavelet transform filter **50** thus includes the low frequency wavelet transform coefficients **13L** from the final low pass filter **42d** and as many sets of high frequency wavelet transform coefficients **13H** as there are high pass filters, for example, four sets corrsponding to the four high pass filters shown in FIG. 2, **41a, 41b, 41c, 41d**.

In the preferred embodiment, the multistage wavelet transform filter **50** contains four stages. The filter coefficients for each of the four low pass filters in the multistage wavelet transform filter **50** are given by

$$H_1 = 0.125 \qquad H_3 = 0.375$$
$$H_2 = 0.375 \qquad H_4 = 0.125$$

The filter coefficients for the four high pass filters are as follows:

Stage1	Stage2	Stage 3	Stage 4
$-2/\lambda_1$	$-2/\lambda_2$	$-2/\lambda_3$	$-2/\lambda_4$
$2/\lambda_1$	$2/\lambda_2$	$2/\lambda_3$	$2/\lambda_4$

where

$$\lambda_1 = 1.50 \qquad \lambda_3 = 1.03$$
$$\lambda_2 = 1.12 \qquad \lambda_4 = 1.01$$

At each stage, the cut-off frequency for the low-pass filter and the cut-off frequency for the high-pass filter are chosen to divide the available frequency band in half as shown in FIG. 4. Thus, at the first stage **50a**, the available frequency band ranges from 0 to $1/2\, f_{Nyq}$ where f_{Nyq} is the Nyquist frequency (equal to twice the bandwidth of the signal). Accordingly, the first high-pass filter **41a** has a filter response **72** which passes frequencies from $1/4\, f_{Nyq}$ to $1/2\, f_{Nyq}$ and the first low-pass filter **42a** has a filter response (not shown) which passes frequencies from 0 to $1/4\, f_{Nyq}$. In the second wavelet transform **50b**, the available frequencies extend from 0 to $1/4\, f_{Nyq}$, hence the second high-pass filter **41b** has a filter response **74** which passes frequencies from $1/8\, f_{Nyq}$ to $1/4\, f_{Nyq}$ and the low-pass filter **42b** passes frequencies from 0 to $1/8\, f_{Nyq}$. This process of subdividing the original spread of available frequencies into sub-bands one octave wide continues with each wavelet transform in the multi-stage wavelet transform filter **50** illustrated in FIG. 2.

At the last stage, the low frequency wavelet transform coefficients **13L** generated by the last low pass filter **42d** are bundled with the four sets of high frequency wavelet transform coefficients **13H** generated by the four high pass filters **41a-41d** to form the output wavelet transform coefficients **13** of the multistage wavelet transform filter **50**. The output wavelet transform coefficients **13** are then passed into an enhancement system **10** which assigns: alternative values to those high frequency wavelet transform coefficients **13H** having a selected property; and adjusted values to the remaining high frequency wavelet transform coefficients **13H** and low frequency wavelet transform coefficients **13L** of the original signal. The manner in which the enhancement system **10** assigns alternative values and adjusted values are described below with reference to FIG. 3.

The enhancement system **10** generates an enhanced signal **39** which is then passed to an iteration controller **43** which can either direct the enhanced signal **39** back into the first multistage wavelet transform filter **50** for further enhancement or send it to an output device such as the monitor **62** shown in FIG. 1. If the iteration controller **43** directs the enhanced signal **39** back into the multistage wavelet transform filter **50**, then the enhanced signal is processed by the multistage wavelet transform filter **50** in the same manner as the original signal **11**.

FIG. 3 is a schematic block diagram of the enhancement system **10** of the invention. The enhancement system **10** inputs the high frequency wavelet transform coefficients **13H** obtained from either the original signal **11** (as shown in FIG. 3) or from an enhanced signal **39** fed back into the multistage wavelet transform filter **50** in the manner set forth above and illustrated in FIG. 2 to a first extractor **14**. The first extractor **14** then extracts from these high frequency wavelet transform coefficients **13H** a table of local maxima $W_j(x_i)$ **15**, where j refers to the stage associated with the particular high pass filter.

By a local maximum, we mean a wavelet transform coefficient having a magnitude in excess of the magnitudes of its neighbors. By way of example, in the video signal illustrated in FIG. 5, the extractor **14** compares the wavelet transform coefficient associated with the illustrated pixel **74** with the wavelet transform coefficients associated with the two adjacent pixels on the same column **74N,74S** with which it shares a common boundary. If the magnitude of the wavelet coefficient transform associated with the illustrated pixel **74** exceeds that of its column neighbors **74N, 74S** then the extractor **14** classifies that wavelet transform coefficient as a local maximum. Similarly, in another embodiment, the extractor **14** compares the illustrated pixel **74** with the wavelet transform coefficients associated with the two adjacent pixels on the same row **74W,74E** with which it shares a common boundary. If the magnitude of the wavelet coefficient transform associated with the illustrated pixel **74** exceeds that of its row neighbors **74W, 74E** then the extractor **14** classifies that wavelet transform coefficient as a local maximum.

The tables of local maxima **15** are then passed to a multiplier **16** for scaling by a scaling constant **17** thereby generating tables of scaled local maxima **18** for input to a swapper **20**. The scaling constant **17** depends on which high pass filter **41a-41d** generated the high frequency wavelet transform coefficients being processed by the extractor **14**. In the preferred embodiment, the high frequency wavelet transform coefficients generated by the first high pass filter **41a** are scaled by 1.6. The high frequency wavelet transform coefficients generated by the second high pass filter **41b** are scaled by 1.8. The high frequency wavelet transform coefficients generated by the third high pass filter **41c** and by the fourth high pass filter **41d** are scaled by 2.0 and 2.5 respectively.

The swapper **20** replaces the local maxima $W_j(x_i)$ **15** from the high frequency wavelet transform coefficients **13H** by the scaled local maxima $c_jW_j(x_i)$ **18**. The set of perturbed coefficients **21** thus created by the combination of the low frequency wavelet transform coefficients **13L** and the output of the swapper **20** is identical to the set of wavelet transform coefficients **13** with the exception that each local maximum from the

high frequency wavelet transform coefficients **13H** has been multiplied by the scaling constant **17** corresponding to the high pass filter **41a-41d** that generated it.

It is known in the art that in order for a set of coefficients $\{a_1, a_2, \ldots a_n\}$ to constitute a set of valid wavelet transform coefficients, certain relationships must exist between the coefficients. These relationships, summarized in *Cody* and previously incorporated by reference, are as follows: For a function $f(x)$ to be represented as a sum of weighted wavelet basis functions:

$$f(x) = \sum_k a_k \Psi_k(t)$$

the a_k must satisfy:

$$\sum_k a_{2k} = 1 \qquad \sum_k a_k a_{k+\bullet} = 0 \text{ for } \bullet \neq 0$$
$$\sum_k a_{2k+1} = 1 \qquad \sum_k a_k \overline{a_k} = 2$$

where $\overline{a_k}$ is the complex conjugate of a_k.

It is apparent, therefore, that if $\{a_1, a_2, \ldots a_n\}$ are valid wavelet transform coefficients **13** satisfying the foregoing relationships, there is no guarantee that replacing any one of the a_k will result in a set of coefficients which continue to satisfy the foregoing relationships. If, for example, a_2 were a local maximum, then the coefficient a_2 in the set of wavelet transform coefficients **13** would be replaced by $c_j a_2$, where c_j is the scaling constant for stage j of the multi-stage wavelet transform filter **50** depicted in FIG. 2. There would then be no guarantee that the resulting set of perturbed coefficients **21**, namely $\{a_1, c_j a_2, \ldots a_n\}$, would continue to satisfy the foregoing conditions. In order to ensure that the perturbed coefficients **21** are still a valid set of wavelet transform coefficients, the wavelet transform coefficients **13** that are not local maxima $W_j(x_i)$ **15** must be adjusted to correct for the perturbation caused by replacing the local maxima with scaled local maxima $c_j W_j(x_i)$ **18**. This adjustment preferably avoids the loss of the signal enhancement associated with having multiplied each local maximum by the scaling constant **17**.

The adjustment process begins by passing the perturbed coefficients **21** to a first multistage inverse wavelet transform filter **22** which performs the inverse of each wavelet transform stage **50a-50d** in the first multistage wavelet transform filter **50**. In the preferred embodiment, the low pass filter coefficients for all four low pass filters used in the multistage inverse wavelet transform filter **22** are as follows:

$$H_1 = 0.125 \qquad H_3 = 0.375$$
$$H_2 = 0.375 \qquad H_4 = 0.125$$

The high pass filter coefficients for the four high pass filters used in the multistage inverse wavelet transform filter are as follows:

Stage1	Stage2	Stage 3	Stage 4
$0.0078125 \cdot \lambda_1$	$0.0078125 \cdot \lambda_2$	$0.0078125 \cdot \lambda_3$	$0.0078125 \cdot \lambda_4$
$0.0546850 \cdot \lambda_1$	$0.0546850 \cdot \lambda_2$	$0.0546850 \cdot \lambda_3$	$0.0546850 \cdot \lambda_4$
$0.1718750 \cdot \lambda_1$	$0.1718750 \cdot \lambda_2$	$0.1718750 \cdot \lambda_3$	$0.1718750 \cdot \lambda_4$
$-0.1718750 \cdot \lambda_1$	$0.1718750 \cdot \lambda_2$	$-0.1718750 \cdot \lambda_3$	$-0.1718750 \cdot \lambda_4$
$-0.0546850 \cdot \lambda_1$	$0.0546850 \cdot \lambda_2$	$-0.0546850 \cdot \lambda_3$	$-0.0546850 \cdot \lambda_4$
$-0.0078125 \cdot \lambda_1$	$-0.0078125 \cdot \lambda_2$	$-0.0078125 \cdot \lambda_3$	$-0.0078125 \cdot \lambda_4$

where

$$\lambda_1 = 1.50 \qquad \lambda_3 = 1.03$$
$$\lambda_2 = 1.12 \qquad \lambda_4 = 1.01$$

The output of the first multistage inverse wavelet transform filter **22** is then passed to a second multistage wavelet transform filter **24** identical to the multistage wavelet transform filter **50** shown in FIG. 2. The second multistage wavelet transform filter **24** performs the same sequence of wavelet transforms performed by the first multistage wavelet transform filter **50** as shown in FIG. 2. This results in a set of estimated coefficients **25**.

It is important to note that despite the manner in which they were generated, the estimated coefficients **25** are not necessarily identical to the perturbed coefficients **21** from which they were derived. This is because the mapping provided by the wavelet transform from the spatial domain to the frequency domain is not one-to-one and onto. The mathematical theory of this aspect of the wavelet transform is discussed in Jian Lu, *Signal Recovery and Noise Reduction with Wavelets*, Ph.D. Thesis, June 1993, Dartmouth College, Hanover, N.H., which is hereby incorporated by reference.

A second extractor **26**, identical to the first extractor **14**, extracts from the estimated coefficients **25** those coefficients located at the rows and columns corresponding to the original local maxima $W_j(x_i)$ **15**. The output of the second extractor **26** is a table of estimates **27** $w_j(x_i)$ having as many entries as there were in the table of local maxima **15**. A first summer **30** substracts the entries from the table of estimates **27** from the corresponding elements of the table of local maxima **15** thereby generating an error table **31**, each element of which corresponds to a sampled value of an error function $\varepsilon_j(x_i)$ evaluated at the locations corresponding to the locations of the local maxima x_i.

The error table **31** corresponding to sampled values of the error function is then passed to an evaluator **32** which derives a function $\varepsilon_j(x)$. This function is chosen such that when added to the perturbed coefficients **21**, the resulting output set of wavelet transform coefficients **37** satisfies two conditions: (1) at the rows and columns corresponding to the local maxima $W_j(x_i)$ **15** of the wavelet transform coefficients of the original image, the output set of wavelet transform coefficients **37** contains the corresponding local maxima **15**; and (2) the sum of the differences between the coefficients of the output set of wavelet transform coefficients **37** and the corresponding coefficients from the wavelet transform coefficients **13** passed to the enhancement system **10** by the multistage wavelet transform filter **50** and the rate of change of the differences between the coefficients of the output set of wavelet transform coefficients **37** and the corresponding coefficients from the wavelet transform coefficients **13** is minimized. The method used by the evaluator **32** to derive such a function $\varepsilon_j(x)$ is set forth below.

Because of condition (1), we require that at those locations x_i associated with the local maxima **15** of the original signal, the error function be constrained to be equal to the difference between the scaled local maximum $c_j\ W_j(x_i)$ **18** of the original signal and the value of the estimated coefficient **27** at the corresponding location. In other words:

$$\varepsilon_j(x_i) = c_j W_j(x_i) - w_j(x_i) \quad \text{for } i = 1 \text{ to } n\_maxima_j$$

where x_i is the i^{th} local maximum and n_maxima_j is the number of local maxima at stage j.

Condition (2) can be satisfied by minimizing, for each gap between consecutive local maxima x_i and x_{i+1}, the definite integral:

$$\int_{x_i}^{x_{i+1}} \left(|\varepsilon_j(x)|^2 + 2^{2j} \left| \frac{d}{dx} \varepsilon_j(x) \right|^2 \right) dx$$

where the second term of the integrand is included to prevent spurious local maxima from distorting the solution.

The above definite integral can be minimized by solving the differential equation

$$\varepsilon_j(x) - 2^{2j} \frac{d^2}{dx^2} \varepsilon_j(x) = 0$$

the general solution of which is:

$$\varepsilon_j(x) = \alpha \exp(2^{-j} x) + \beta \exp(-2^{-j} x)$$

The constants α and β are then chosen to satisfy the boundary conditions imposed by condition (1) at x_i and x_{i+1}. The resulting α and β are given by

$$\alpha = \frac{\varepsilon_j(x_i)\exp(-2^{-j}x_{i+1}) - \varepsilon_j(x_{i+1})\exp(-2^{-j}x_i)}{\exp(2^{-j}x_i - 2^{-j}x_{i+1}) - \exp(2^{-j}x_{i+1} - 2^{-j}x_i)}$$

and

$$\beta = (\varepsilon_j(x_i) - \alpha\exp(2^{-j}x_i))\exp(2^{-j}x_i)$$

The output of the error function evaluator **32** is an error function $\varepsilon(x)$ **33** which can be added to the perturbed coefficients **21** at a second summer **34**. The result of this addition is a set of output wavelet transform coefficients **37** satisfying the two conditions set forth above and corresponding to an enhanced signal **39**. This set of output wavelet transform coefficients **37** is then passed to a second multistage inverse wavelet transform filter **36** identical to the first multistage transform filter **22**. The second multistage inverse wavelet transform filter **36** performs the inverse of each wavelet transform stage **50a-50d** performed by the first multistage wavelet transform filter **50** thereby generating the enhanced signal **39**.

Referring now to FIG. 2, the resulting enhanced signal **39** corresponding to the original image **11** can then be directed by the iteration controller **43** to an output device such as the monitor **62** shown in FIG. 1. Alternatively, the resulting enhanced signal **39** can be fed back, by the iteration controller **43**, into the first multistage wavelet transform filter as shown in FIG. 2 for further enhancement and the process repeated iteratively either a predefined number of times or until the error has been reduced below a predefined level.

The foregoing system can be used to enhance, in a variety of different ways, a one dimensional signal, such as an audio signal, or an *n*-dimensional signal.

Different enhancement results can be achieved by emphasizing specific frequency bands relative to the entire signal bandwidth. For example, instead of extracting a table of local maxima, the first extractor **14** can extract wavelet transform coefficients having other selected properties. The first extractor **14** can, for example, extract a table of those coefficients exceeding a specified value or a table of those coefficients falling within a range of values.

The assignment of an alternative value to the coefficients classified by the first extractor **14** as having a selected property can likewise take on many forms. For example, instead of multiplying the coefficient by a constant **17** to obtain an alternative value **18**, as depicted in FIG. 3, one could obtain an alternative value **18** by adding an offset or by convolving the selected coefficient with a predefined sequence.

For those coefficients lacking the selected property, the step of assigning an adjustment value can also be altered without departing from the scope of the invention. For example, a different integrand can be used or different boundary conditions can be imposed by the evaluator **32**.

When processing a signal representative of an image as shown in FIG. 5, the first extractor **14** determines whether a particular wavelet transform coefficient **74** is a local maximum by comparing its value by that of its adjacent neighbors, either in the same row **74R** or in the same column **74C**, but preferably not both. Further enhancement of the image can, however, be achieved by comparing the value of the wavelet transform coefficient **74** with values of wavelet transform coefficients in both the same row **74R** and in the same column **74C**. This can be implemented by passing the output of the first enhancement system **10** to a second multistage wavelet transform filter **52** as shown in FIG. 6. The output of the second wavelet transform filter **52** is then passed to a second enhancement system **12** similar to that shown in FIG. 2 with the exception that the first extractor **14** obtains local maxima by comparing each pixel with those adjacent pixels not used by the first extractor of the first enhancement system **10**. Thus, if the first enhancement system **10** were to obtain local maxima by comparing each pixel **74** with adjacent pixels on the same row **74E**, **74W**, the second enhancement system **12** would obtain local maxima by comparing each pixel **74** with those adjacent pixels in the same column **74N**, **74S**. Conversely, if the first enhancement system **10** were to obtain local maxima by comparing each pixel **74** with adjacent pixels on the same column **74N**, **74S**, the second enhancement system **12** would obtain local maxima by comparing each pixel **74** with those adjacent pixels in the same row **74E**, **74W**.

The wavelet transform coefficients generated by the second multistage wavelet transform filter **52** are passed to a second enhancement system **12** identical to the first enhancement system **10** with the exception that the extractor associated with the second enhancement system **12** determines whether a particular wavelet transform coefficient **74** is a local maximum by comparing it with its neighbors in the direction orthogonal to that used by the extractor in the first enhancement system **10**. For example, if the first enhancement system **10** determines whether a wavelet transform coefficient **74** is a local maximum by comparing it with its neighbors **74E**, **74W** in the same row **74R**, the second enhancement system **12** will determine whether a particular wavelet transform coefficient **74** is a local maximum by comparing it with its neighbors **74N**, **74S** in the same column **74C**. Conversely, if the first enhancement system **10** determines whether a particular wavelet transform coefficient **74** is a local maximum by comparing it with its neighbors **74N**, **74S** in the same column **74C**, then the second enhancement system **12**

will determine whether a particular wavelet transform coefficient **74** is a local maximum by comparing it with its neighbors **74E**, **74W** in the same row **74R**.

It is thus seen that the invention efficiently attains the objectives set forth above, among those made apparent from the preceding description. Since certain changes may be made in the above constructions without departing from the scope of the invention, it is intended that all matter contained in the above description or shown in the accompanying drawings be interpreted as illustrative and not in a limiting sense.

It is also to be understood that the following claims are to cover all generic and specific features of the invention described herein, and all statements of the scope of the invention which, as a matter of language, might be said to fall therebetween.

Having described the invention and a preferred embodiment thereof, what is claimed as new and secured by Letter Patent is:

We Claim:

1. A method for generating, on a computer system, an enhanced signal from an original signal, said original signal being represented by a first set of wavelet transform coefficients including at least one coefficient having a selected property and at least one coefficient lacking said selected property and said enhanced signal being represented by a second set of wavelet transform coefficients, said method comprising the steps of:

replacing said at least one coefficient having a selected property with an alternative value, thereby forming a set of alternative coefficients; and

replacing said at least one coefficient lacking said selected property with an adjusted value, thereby forming a set of adjusted coefficients, said adjusted value being chosen such that said set of adjusted coefficients and said set of alternative coefficients define a second set of wavelet transform coefficients representative of said enhanced signal.

2. The method of claim 1, further comprising the step of selecting said original signal to be a video signal, an audio signal, or an audiovisual signal, and optionally wherein said alternative value is the product of a predefined scaling constant and said at least one coefficient having said selected property.

3. The method of claim 1 or claim 2, wherein said at least one coefficient having said selected property acquires said selected property independently of the values of the remaining coefficients from said first set of wavelet transform coefficients.

4. The method of any of the preceding claims, wherein said selected property is the property of being a local maximum of said first set of wavelet transform coefficients and wherein said step of replacing said at least one coefficient having said selected property further comprises the step of determining whether a candidate coefficient from said first set of wavelet transform coefficients is a local maximum.

5. The method of any of the preceding claims, wherein said selected property is the property of having a value such that the difference between said value and a value of a different wavelet transform coefficient from said first set of wavelet transform coefficients exceeds a threshold.

6. The method of any of the preceding claims, wherein said step of replacing said at least one coefficient having a selected property includes the step of determining whether a candidate coefficient has said selected property by comparing the value of said candidate coefficient with the value of at least one neighboring coefficient from said first set of wavelet transform coefficients.

7. The method of any of the preceding claims, wherein said first set of wavelet transform coefficients comprises a neighboring coefficient adjacent to said candidate coefficient, and/or optionally

wherein said adjusted value is further chosen to minimize an average difference between said alternative coefficients and said set of wavelet transform coefficients lacking said selected property.

8. The method of any of the preceding claims, further comprising the step of selecting said adjusted value to minimize an average of a sum of a first term comprising a difference between said alternative coefficients and said set of wavelet transform coefficients lacking said selected property and a second term comprising the rate of change of said difference.

9. The method of any of the preceding claims, wherein said step of replacing said at least one coefficient lacking said selected property comprises the step of

applying to said alternative coefficients the inverse of the wavelet transform used to obtain said first set of wavelet transform coefficients from said signal, thereby generating a set of inverse wavelet transform coefficients, and optionally the step of

generating a set of estimated coefficients by applying to said inverse wavelet transform coefficients a wavelet transform identical to the wavelet transform used to obtain said first set of wavelet transform coefficients, and optionally wherein said evaluating step further comprises the steps of

indexing said set of estimated coefficients and said set of alternative coefficients,

determining an index corresponding to said at least one coefficient having said selected property, and

extracting, from said set of estimated coefficients, a corresponding estimated coefficient associated with said index.

10. The method of any of the preceding claims, wherein said step of replacing said at least one coefficient lacking said selected property with an adjusted value comprises the step of selecting a correction function such that said second set of wavelet transform coefficients:

includes said alternative coefficient at a location corresponding to the location of said at least one coefficient having said selected property; and

minimizes an error between said second set of wavelet transform coefficients and said first set of wavelet transform coefficients evaluated at at least one location other than said location corresponding to said at least one coefficient having said selected property, and optionally comprising the step of

selecting said correction function to minimize the rate of change of said error between said second set of wavelet transform coefficients and said first set of wavelet transform coefficients evaluated at at least one location other than said location corresponding to the location of said at least one wavelet transform coefficient having said selected property in said first set of wavelet transform coefficients.

11. The emthod of claim 1, wherein said step of replacing said at least one coefficient having a selected property comprises the steps of

generating a set of estimated coefficients by evaluating a wavelet transform of an inverse wavelet transform of said set of alternative coefficients, said set of estimated coefficients having an element corresponding to said at least one coefficient having said selected property,

evaluating the difference between said at least one coefficient having said selected property and said element corresponding to said at least one coefficient having said selected property, and

deriving a set of values of a correction function which when added to said set of alternative coefficients results in said set of wavelet transform coefficients representative of said enhanced version of said signal, and optionally

wherein said alternative value is the product of a predefined scaling constant and said at least one coefficient having said selected property.

12. The method of claim 11, further comprising the step of choosing said selected property to be the property of being a local maximum of said first set of wavelet transform coefficients and wherein said step of replacing said at least one coefficient having said selected property includes the step of determining whether a candidate coefficient from said first set of wavelet transform coefficients is a local maximum, and optionally wherein said determining step includes the step of comparing the value of said candidate coefficient with that of a neighboring coefficient from said first set of wavelet transform coefficients.

13. The method of claim 11 or claim 12, wherein said at least one coefficient having said selected property acquires said property independently of the values of the remaining coefficients from said first set of wavelet transform coefficients.

14. The method of claims 11 to 13, further comprising the step of choosing said selected property to be the property of having a value between a first threshold value and a second threshold value, and optionally

wherein said selected property is the property of having a value such that the difference between said value and a value of a different wavelet transform coefficient from said first set of wavelet transform coefficients exceeds a threshold value.

15. The method of claims 11 to 14, wherein said evaluating step further comprises the steps of

indexing said set of estimated coefficients and said set of alternative coefficients,

determining an index corresponding to said at least one coefficient having said selected property, and

extracting, from said set of estimated coefficients, an estimated coefficient corresponding to said index, and optionally the step of

subtracting said at least one coefficient having said selected property from said corresponding estimated coefficient.

16. The method of claims 11 to 15, wherein said deriving step further comprises the step of selecting said correction function such that said second set of wavelet transform coefficients,

includes said alternative coefficient at a location corresponding to the location of said at least one coefficient having said selected property, and

minimizes an error between said second set of wavelet transform coefficients and said first set of wavelet transform coefficients evaluated at at least one location other than said location corresponding to said at least one coefficient having said selected property, and optionally the step of

selecting said correction function to minimize the rate of change of said error between said second set of wavelet transform coefficients and said first set of wavelet transform coefficients evaluated at at least one location other than said location corresponding to the location of said at least one wavelet transform coefficient having said selected property in said first set of wavelet transform coefficients.

17. The method of claim 16, wherein said deriving step further comprises the step of selecting said correction function to be a solution to a membrane equation.

18. The method of claim 11, wherein said step of replacing said at least one coefficient having a selected property comprises the step of replacing said at least one local maximum by a scaled local maximum thereby forming a perturbed set of wavelet transform coefficients, and optionally

said step of generating a set of estimated coefficients by evaluating a wavelet transform of an inverse wavelet transform of said set of alternative coefficients comprises the step of generating a set of estimated coefficients by evaluating a wavelet transform of an inverse wavelet transform of said perturbed set of wavelet transform coefficients, said set of estimated coefficients having an element corresponding to said scaled local maximum, and optionally

said step of evaluating the difference comprises the step of evaluating the difference between said scaled local maximum and said element corresponding to said scaled local maximum, and optionally

said step of deriving said set of values of said correction function comprises the step of adding said values of said correction function to said set of perturbed wavelet transform coefficients to generate said set of wavelet transform coefficients representative of said enhanced version of said signal.

19. The method of claim 18, wherein said first set of wavelet transform coefficients comprises rows and columns of an image and said neighboring coefficient is on the same row as said candidate coefficient, and optionally wherein said neighboring coefficient is adjacent to said candidate coefficient.

20. A system for generating an enhanced signal from an original signal, said original signal being represented by a first set of wavelet transform coefficients including at least one coefficient having a selected property and at least one coefficient lacking said selected property and said enhanced signal being represented by a second set of wavelet transform coefficients, said system comprising:

first replacing means for replacing said at least one coefficient having a selected property with an alternative value, thereby forming a set of alternative coefficients, and

second replacing means for replacing said at least one coefficient lacking said selected property with an adjusted value, thereby forming a set of adjusted coefficients, said adjusted value being chosen such that said set of adjusted coefficients and said set of alternative coefficients define a second set of wavelet transform coefficients representative of said enhanced signal.

21. The system of claim 20, wherein said alternative value is the product of a predefined scaling constant and said at least one coefficient having said selected property, and/or

wherein said at least one coefficient having said selected property acquires said selected property independently of the values of the remaining coefficients from said first set of wavelet transform coefficients, and/or

wherein said selected property is the property of being a local maximum of said first set of wavelet transform coefficients and wherein said first replacing means further comprises means for determining whether a candidate coefficient from said first set of wavelet transform coefficients is a local maximum, and/or

wherein said selected property is the property of having a value such that the difference between said value and a value of a different wavelet transform coefficient from said first set of wavelet transform coefficients exceeds a threshold.

22. The system of claim 20 or claim 21, wherein said first replacing means comprises means for determining whether a candidate coefficient has said selected property by comparing the value of said candidate coefficient with the value of at least one neighboring coefficient.

23. The system of claims 20 to 22, further comprising means for selecting said adjusted value to minimize an average difference between said alternative coefficients and said set of wavelet transform coefficients lacking said selected property, and/or further comprising

means for selecting said adjusted value to minimize an average of a sum of a first term comprising a difference between said alternative coefficients and said set of wavelet transform coefficients lacking said selected property and a second term comprising the rate of change of said difference.

24. The system of claims 20 to 23, wherein said second replacing means comprises means for applying to said alternative coefficients the inverse of the wavelet transform used to obtain said first set of wavelet transform coefficients from said signal, thereby generating a set of inverse wavelet transform coefficients, and optionally comprises

means for generating a set of estimated coefficients by applying to said inverse wavelet transform coefficients a wavelet transform identical to the wavelet transform used to obtain said first set of wavelet transform coefficients.

25. The system of claims 20 to 24, wherein said second replacing means further comprises

means for indexing said set of estimated coefficients and said set of alternative coefficients,

means for determining an index corresponding to said at least one coefficient having said selected property, and

means for extracting, based on said index, the value of a corresponding estimated coefficient from said set of estimated coefficients.

26. The system of claims 20 to 25, wherein said second replacing means comprises means for selecting a correction function such that said second set of wavelet transform coefficients:

includes said alternative coefficient at a location corresponding to the location of said at least one coefficient having said selected property, and

minimizes an error between said second set of wavelet transform coefficients and said first set of wavelet transform coefficients evaluated at at least one location other than said location corresponding to said at least one coefficient having said selected property, and optionally comprises

means for selecting said correction function to minimize the rate of change of said error between said second set of wavelet transform coefficients and said first set of wavelet transform coefficients evaluated at at least one location other than said location corresponding to the location of said at least one wavelet transform coefficient having said selected property in said first set of wavelet transform coefficients.

27. The system of claim 20, wherein said second replacing means comprises

means for generating a set of estimated coefficients by evaluating a wavelet transform of an inverse wavelet transform of said set of alternative coefficients, said set of estimated coefficients having an element corresponding to said at least one coefficient having said selected property,

means for evaluating the difference between said at least one coefficient having said selected property and said element corresponding to said at least one coefficient having said selected property, and

means for deriving a set of values of a correction function which when added to said set of alternative coefficients results in said set of wavelet transform coefficients representative of said enhanced version of said signal, and optionally

wherein said alternative value is the product of a predefined scaling constant and said at least one coefficient having said selected property.

28. The system of claim 27, wherein said selected property is the property of being a local maximum of said first set of wavelet transform coefficients and wherein said replacing means further comprises means for determining whether a candidate coefficient from said first set of wavelet transform coefficients is a local maximum.

29. The system of claim 27 or claim 28, wherein said at least one coefficient having said selected property acquires said property independently of the values of the remaining coefficients from said first set of wavelet transform coefficients.

30. The system of claims 27 to 29, wherein said selected property is the property of having a value such that the difference between said value and a value of a different wavelet transform coefficient from said first set of wavelet transform coefficients exceeds a threshold value.

31. The system of claim 28, wherein said determining means includes means for comparing the value of said candidate coefficient with that of a neighboring coefficient from said first set of wavelet transform coefficients.

32. The system of claims 27 to 31, wherein said evaluating means further comprises

means for indexing said set of estimated coefficients and said set of alternative coefficients,

means for determining an index corresponding to said at least one coefficient having said selected property, and

means for extracting the value of a corresponding estimated coefficient from said set of estimated coefficients corresponding to said index.

33. The system of claims 27 to 32, wherein said deriving means further comprises means for selecting said correction function such that said second set of wavelet transform coefficients:

includes said alternative coefficient at a location corresponding to the location of said at least one coefficient having said selected property, and

minimizes an error between said second set of wavelet transform coefficients and said first set of wavelet transform coefficients evaluated at at least one location other than said location corresponding to said at least one coefficient having said selected property, and optionally

wherein said deriving means further comprises means for selecting said correction function to minimize the rate of change of said error between said second set of wavelet transform coefficients and said first set of wavelet transform coefficients evaluated at at least one location other than said location corresponding to the location of said at least one wavelet transform coefficient having said selected property in said first set of wavelet transform coefficients.

34. The system of claim 27, wherein said first replacing means comprises third replacing means for replacing said at least one local maximum by a scaled local maximum thereby forming a perturbed set of wavelet transform coefficients, and optionally

wherein said generating means comprises second generating means for generating a set of estimated coefficients by evaluating a wavelet transform of an inverse wavelet transform of said perturbed set of wavelet transform coefficients, said set of estimated coefficients having an element corresponding to said scaled local maximum, and optionally

wherein said evaluating means comprises second evaluating means for evaluating the difference between said scaled local maximum and said element corresponding to said scaled local maximum, and optionally

wherein said deriving means comprises second deriving means for deriving a set of values of a correction function which when added to said set of perturbed wavelet transform coefficients results in said set of wavelet transform coefficients representative of said enhanced version of said signal.

35. The system of claim 34, further comprising

means for indexing said set of estimated coefficients and said set of perturbed wavelet transform coefficients,

means for determining an index corresponding to said scaled local maximum, and

means for extracting the value of the corresponding element from said set of estimated coefficients corresponding to said index.

36. The system of claim 34, wherein said second deriving means further comprises means for selecting said correction function such that said second set of wavelet transform coefficients:

includes said scaled local maximum at a location corresponding to the location of said at least one local maximum in said first set of wavelet transform coefficients, and

minimizes an error between said second set of wavelet transform coefficients and said first set of wavelet transform coefficients evaluated at at least one location other than said location corresponding to the location of said at least one local maximum, and optionally

wherein said second deriving means further comprises means for selecting said correction function to minimize the rate of change of said error between said second set of wavelet transform coefficients and said first set of wavelet transform coefficients evaluated at at least one location other than said location corresponding to the location of said at least one local maximum in said first set of wavelet transform coefficients.

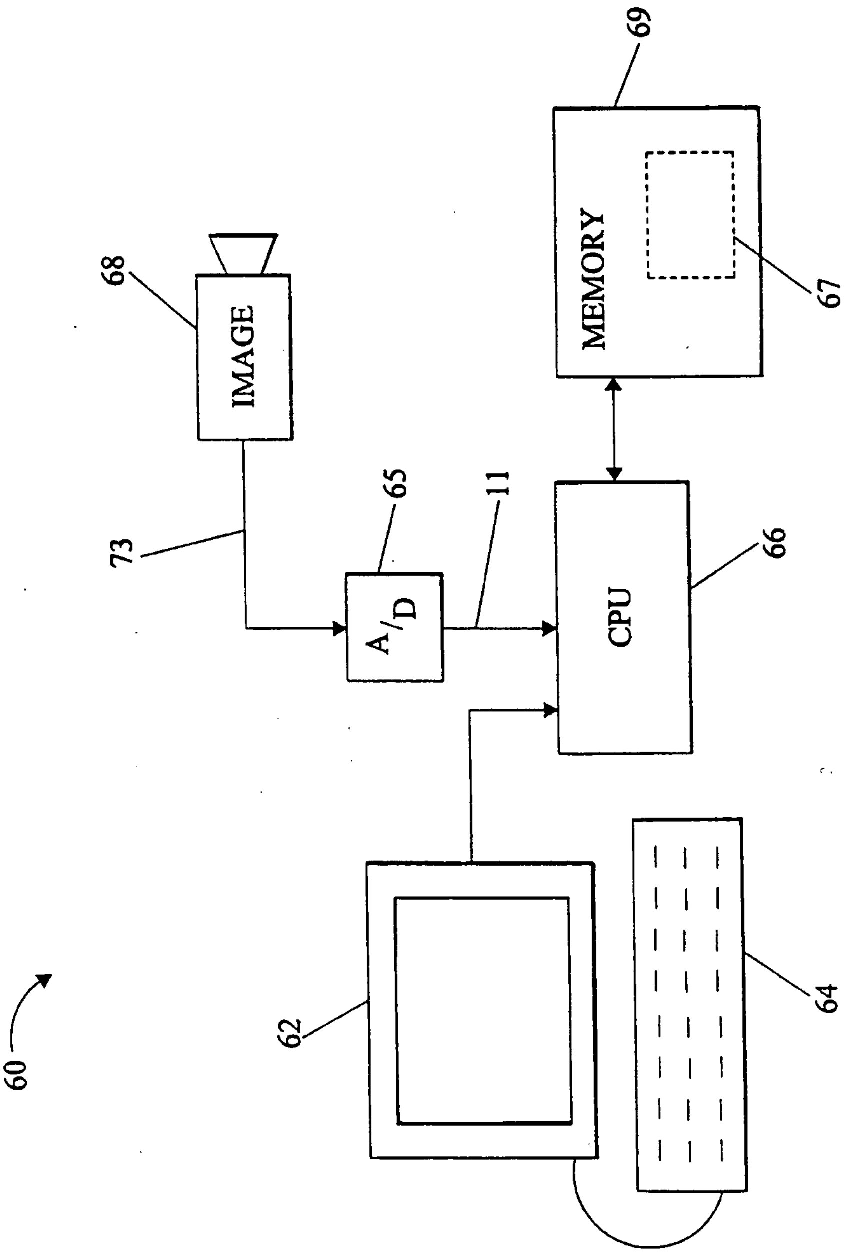
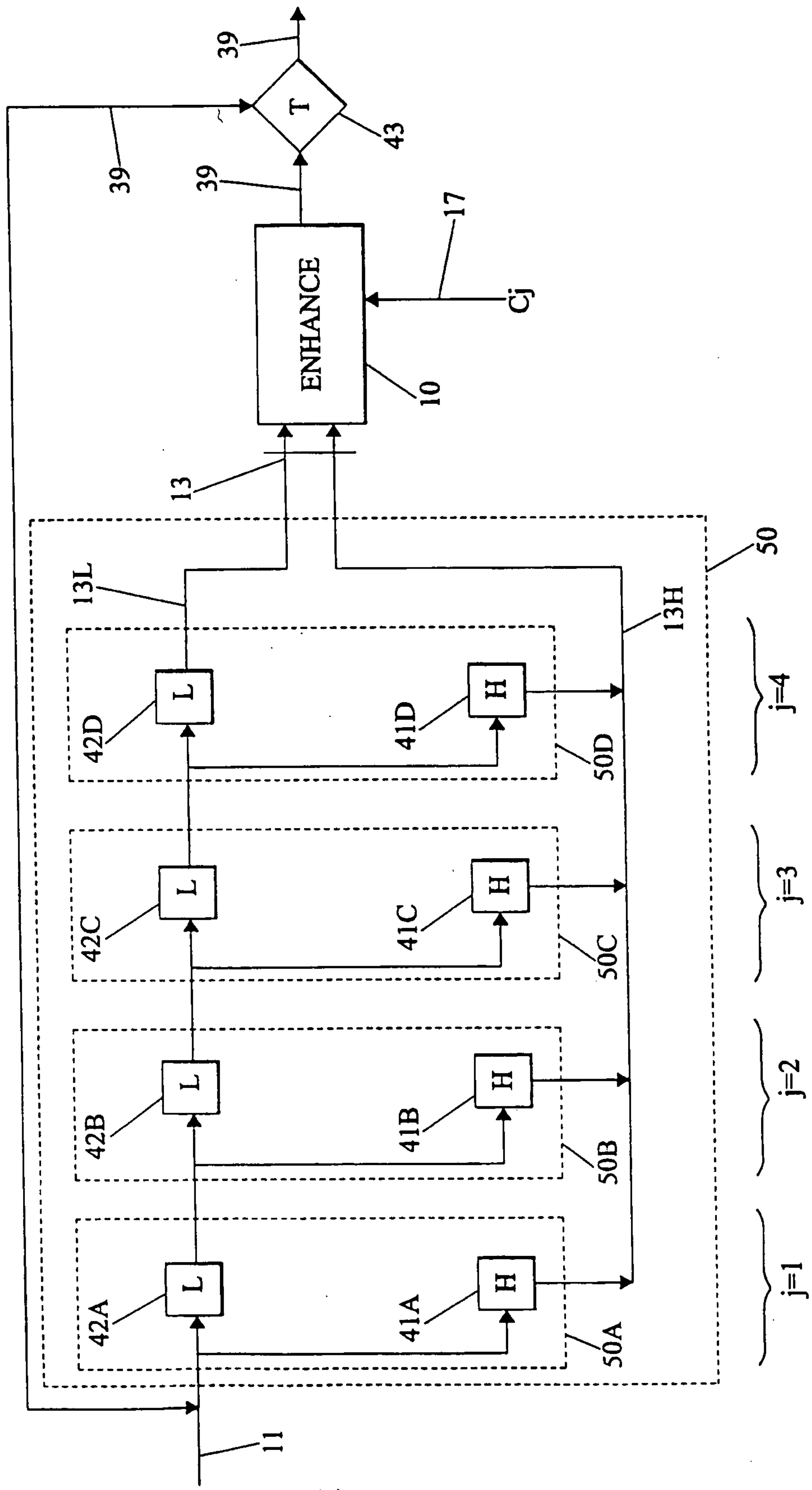


FIG. 1

2/6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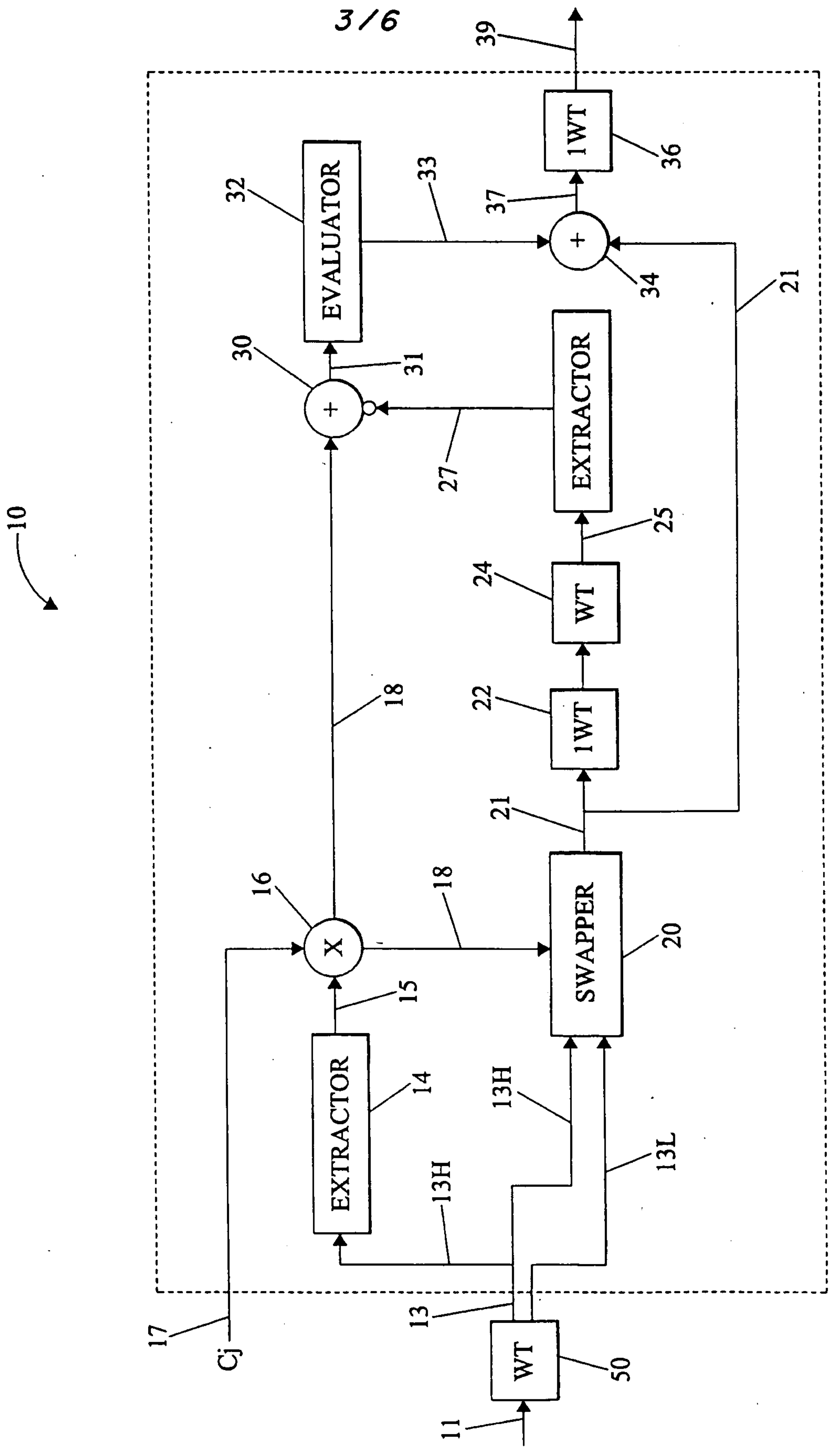
j=1
11

FIG. 2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Cj
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X
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18
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21
1WT
22
WT
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+
30
31
EVALUATOR
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33
+
34
37
1WT
36
39
21

FIG. 3

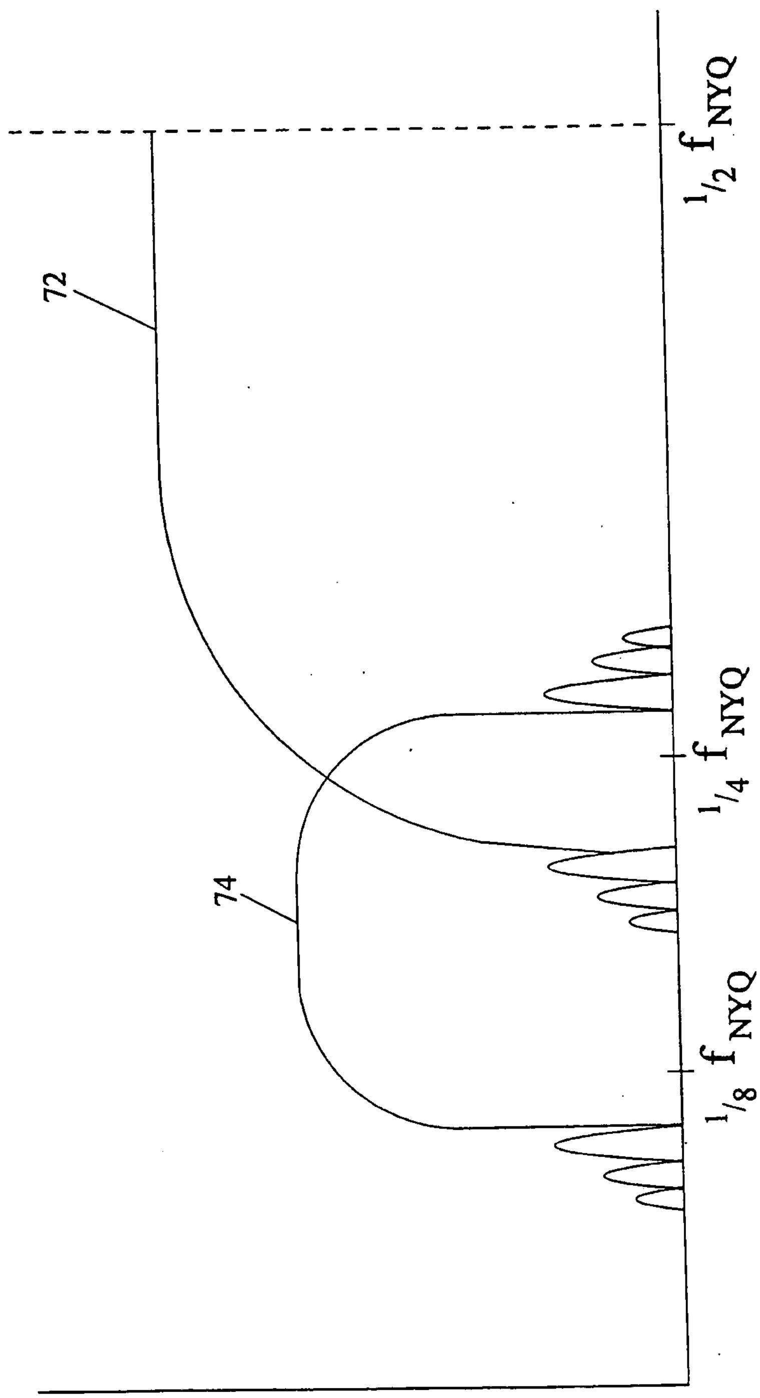


FIG. 4

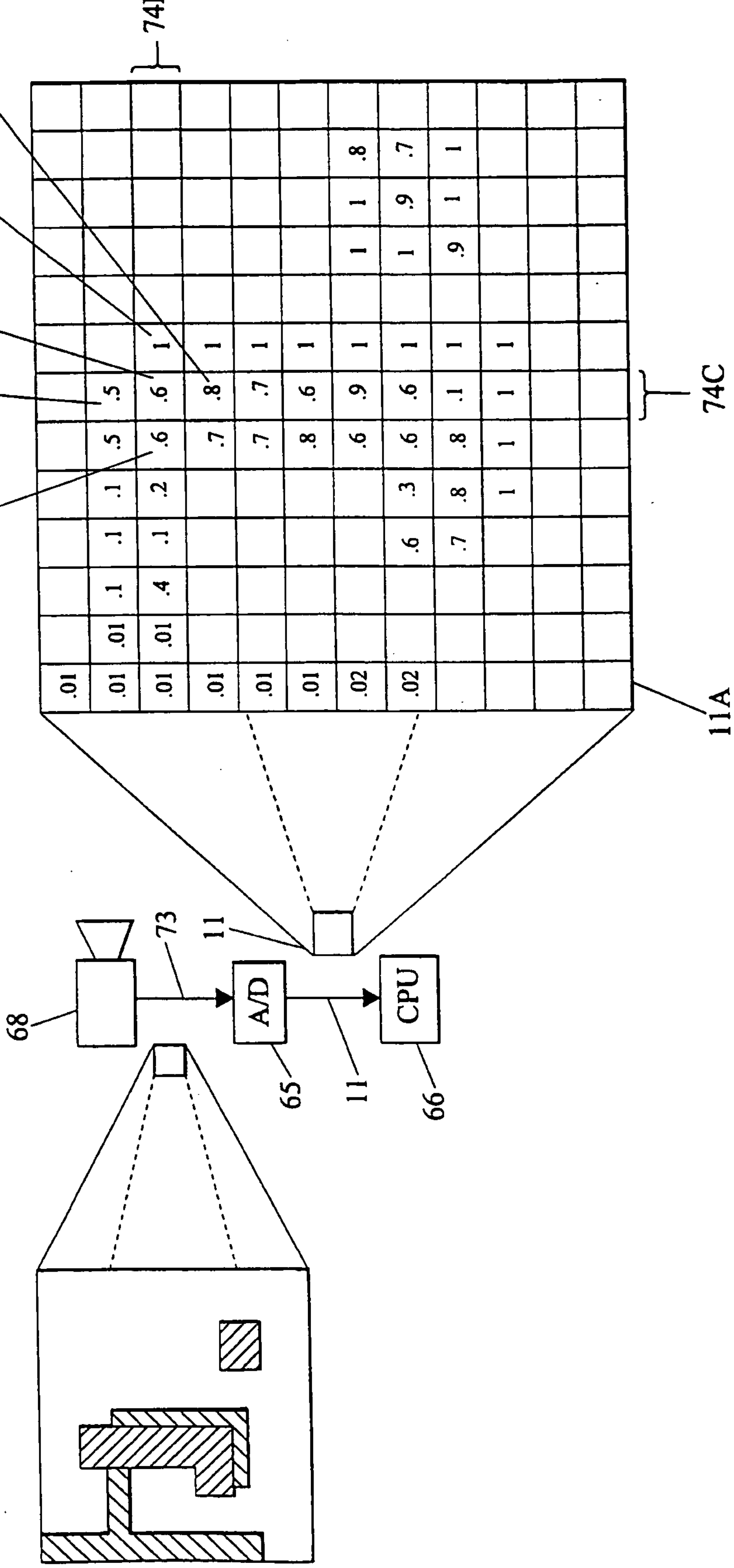
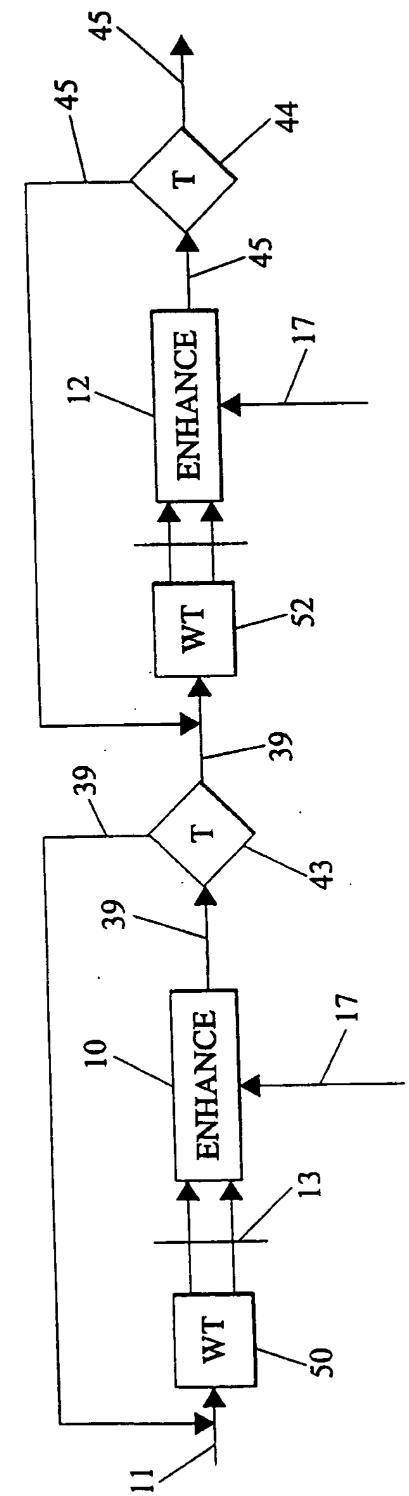


FIG. 5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11

FIG. 6

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 98/25590

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G06T5/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G06T

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5 497 777 A (ABDEL-MALEK AIMAN A ET AL) 12 March 1996 see abstract see column 5, line 18 - column 6, line 41 ---	1-36
Y	US 5 619 998 A (ABDEL-MALEK AIMAN A ET AL) 15 April 1997 see column 2, line 35 - line 52 see column 5, line 55 - column 6, line 62; claims 1-8 ---	1-36
A	EP 0 712 092 A (AGFA GEVAERT NV) 15 May 1996 see abstract see page 3, line 2054 -----	1-36

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
27 April 1999	06/05/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Gonzalez Ordonez, O

INTERNATIONAL SEARCH REPORT

.nformation on patent family members

Inter   ›nal Application No
PCT/US 98/25590

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